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Resilient urban forms: A review of literature on streets and street networks

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ABSTRACT

Cities need to build on their resilience to deal with the combined effects of urbanization, changing geopolitical contexts, and climate change. The physical form of cities has significant implications for their capacity to deal with adverse events and changing conditions. This paper focuses on streets as major constituent elements of urban form. It offers a review of the theoretical discussions and empirical evidence on how design and configuration of urban streets and street networks can contribute to/detract from urban resilience. For the purpose of this study, measures related to urban streets are divided into two broad categories: network topology and design and orientation. Network topology is used to represent urban street network as a combination of nodes and links. Relationships between urban resilience and different centrality and connectivity measures related to network topology are discussed. The design and orientation category explores the possible effects of street width, street edges, street canyon geometry, and street layout and orientation on resilience of cities. It is discussed that all topology and design measures have implications for urban resilience. Appropriate physical form of urban streets can contribute to urban resilience by, among other things, ameliorating urban microclimate, reducing energy consumption and its associated Greenhouse Gas (GHG) emissions, enhancing social capital, improving community health and well-being, and facilitating rapid and effective emergency response in the aftermath of disasters. Overall, results provide insights about physical properties that are required to design resilient streets and street networks.

1. Introduction

The convergence of urbanization, changing geopolitical contexts and climate change is considered as a critical challenge confronting urban areas around the world, where the majority of the world population lives. The impacts of this convergence can have a significant bearing on appropriate functioning of urban areas as primary engines of innovation and economic growth.

In view of these potential threats, cities around the world are increasingly recognizing the significance of building on their resilience. Meanwhile, planning efforts aimed at enhancing urban resilience are informed by a vast body of research that deals with multiple dimensions of urban resilience [1]. Focus has been primarily on non-physical aspects, particularly related to environmental, social, institutional, and economic dimensions of resilience [2]. Research on physical aspects is mainly related to infrastructure resilience (including building, transportation, water, and energy systems) [3,4]. In comparison, a relatively under-explored area is how the physical form of cities can contribute/detract from urban resilience.

United Nations projections show that about 66% of the world's population will live in cities by 2050 (an increase of nearly 12% relative to the 2014 baseline proportion). In other words, about 2.5 billion people will be added to the urban population and majority of this growth will occur in urban areas of African and Asian developing countries [5]. This means that the physical stock of cities is likely to expand significantly in the next three decades. As the physical structure of cities is long lived, it can introduce inertia into planning efforts aimed at creating resilient cities.

Research on urban form aims at understanding the dynamics and complexities of the physical structure of cities. Urban from can be defined as the physical and spatial representation of human activities in cities that involve complex interactions between various socio-economic, technological, and environmental factors [6–9]. The constituent elements of urban form can be classified into different categories related to different scales. For instance, macro-level elements are related to the overall structure and size of the city, development type, distribution pattern of population and employment, and degree of clustering [9]. Micro/meso level elements are concerned with design and arrangement of other elements such as buildings, open spaces, blocks, neighborhoods, and streets [9]. In this study I only focus on elements related to streets and street networks.

Streets and road networks are the backbones of cities. They are fundamental for emergence of cities and guide their growth and evolution. They are among the most long-lived components of urban form

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and can stay in place for decades and even centuries. Therefore, their design and structure is likely to lock urban systems into either negative or positive pathways. Lock-in into negative pathways undermines the capacity of cities to adapt to changing conditions that may arise because of adverse events or social and technological transformations. Further, as components that bind different constituent elements of urban structure into a coherent functional whole, streets have significant implications for proper functioning of existing infrastructure and for future development and operation of other types of urban infrastructure (e.g., energy grid or communication networks). Indeed, undesirable street patterns will constrain future development of such infrastructure [10].

Disasters and adverse events are likely to have significant impacts on the performance of streets and street networks [11]. Therefore, it is critical to structure streets in a way that facilitates resilience to changing conditions with minimum need for making major structural changes. Against this background, the main objective of this paper is to contribute to filling the gap in research on the role of urban form in achieving urban resilience by examining how design and structure of streets and street networks relates to urban resilience. To that end, this paper discusses how network topology factors such as centrality and connectivity, along with design-related factors such as street width, design of street edges, and street layout and orientation can play a significant role in enabling cities to deal with adverse events and changing conditions.

The paper is structured as follows: research methods and materials are explained in Section 2. Section 3 explores the implications of network topology and street design for achieving urban resilience. In the final section, a synthesis of the discussions is provided and some ideas for future research are suggested.

2. Methods and materials

Resilience is a relatively new, but increasingly popular concept in the field of urban studies [12,13]. Three commonly recognized approaches towards defining resilience are: engineering resilience, ecological resilience, and evolutionary resilience [4,12,13]. Engineering resilience focuses on the stability, resistance, and robustness capacities of the system and entails a rapid return to an equilibrium state after experiencing shocks and/or stresses. This is a commonly used approach in many conventional planning policies and practices that assume disasters are predictable and blueprint strategies can be used to deal with them [4,12,14]. In contrast, ecological resilience focuses on the persistence of the system and its capacity to retain its main structure and functions when facing adverse conditions. According to this conceptualization, the system may shift to a new equilibrium state (s) during the recovery process [4,12]. The third and most recent approach is in stark contrast with the conventional planning approaches. It recognizes the non-linearity, complexity, and dynamism of the system and acknowledges the insufficiency of static approaches for dealing with uncertainties. Based on this approach, a resilient system constantly undergoes transformation and this enables it to maintain the essential functions when dealing with shocks. Furthermore, during the recovery phase, the system may transform into a new and more desirable regime (instead of returning to equilibrium state(s)) [4,12]. Sometimes referred to as socio-ecological or adaptive resilience, evolutionary resilience recognizes the importance of paying attention to other essential resilience characteristics such as adaptability, flexibility, foresight capacity, self-organization, collaboration, diversity, redundancy, efficiency, modularity, and innovation (see the cited references for the definition of these characteristics) [1,4,12,14].

Due to its holistic approach towards resilience characteristics which makes it more suitable for addressing the conventional planning shortcomings, the evolutionary approach is more suitable for guiding efforts towards improving resilience of streets and street networks (as essential components of urban form). This is because, for instance, while conventional planning mainly focuses on robustness of street networks and their effectiveness for vehicular movement, paying attention to other issues such as flexibility, efficiency, redundant capacity, and social vibrancy is needed for redefining streets and street networks from a resilience perspective [14]. However, as discussed earlier, urban form resilience is still an under-explored branch of urban resilience [9,14]. While form-based physical components may seem to be rigid and in contrast with resilience characteristics, their implications for achieving urban resilience may be significant. Therefore, in applying the resilience concept to the study of urban form (with focus on streets and street networks in this paper) it can be assumed that physical design of cities can support maintaining urban integrity and functionality under constantly changing conditions and can influence capacity of cities to plan and prepare for, absorb, recover from, and more successfully adapt to shocks and adverse events [14,15]. Such shocks and adverse events may have diverse origins and may be related to sub-categories such as natural disasters, environmental and climatic shocks and stressors, social shocks and stressors, economic shocks and stressors, technology-related shocks and failures, and shocks related to deliberate actions such as sabotage and terrorism.

Based on these discussions a framework can be developed to analyze resilience of physical components related to streets and street networks (Fig. 1). The framework is guided by these four questions: 'resilience of what?' (physical components of streets and street networks), 'resilience to what?' (different categories of shocks), 'resilience at what stage?' (planning, absorption, recovery, and adaptation), and 'resilience for what?' (resilience characteristics such as diversity, redundancy, etc.). It is worth noting that this study does not intend to cover all the components of this framework. The objective is to discuss related theoretical and empirical evidence that is reported in the reviewed literature. However, the framework can be used to collect further evidence in the future and provide a more comprehensive analysis.

This research relies on theoretical and empirical evidence found in the literature to elaborate on the key concepts and typologies related to resilience of urban streets and street networks. For this purpose, it is needed to retrieve literature published on this topic. Therefore, a broad-based search strategy was developed that was mainly guided by the following three fundamental questions pertinent to the study of resilience: 'resilience of what?' and 'resilience to what?', and 'resilience at what stage?'. In response to the first question, major components of streets and street networks [16] were included in the search query. To address the second question, the search query was structured in a way to cover a broad range of disasters and adversities that can threaten current and future functionality of urban systems. The third question is addressed by including terms related to different stages of resilience planning. The final search query, which is a combination of strings pertinent to these three questions, and terms related to the concept of resilience can be found in the Supplementary Appendix.

The 'advanced search' function of the Web of Science was used to retrieve all types of English-language documents that match the search criteria. The search was done for an unrestricted time period and yielded 207 papers. 176 papers remained in the database after excluding categories that were not related to the research question (e.g., mining, biology, biodiversity conservation, etc.). Abstracts of the remaining articles were reviewed to determine if they are relevant for the study of urban street resilience. Papers that were directly related to the main objectives of the study were selected for in depth content analysis. Since only searching 'title, abstracts, and keywords' may result in the exclusion of some relevant documents, while analyzing these papers, relevant research cited by them was also downloaded and added to the review database (see Table 1 of the supplementary appendix for an overview of the core studies). To analyze the contents, theoretical discussions and empirical evidence related to each of the street elements were extracted from the reviewed literature. In this paper, empirical evidence refers to any evidence reported based on real-world observations and/or simulation results. The extracted evidence was

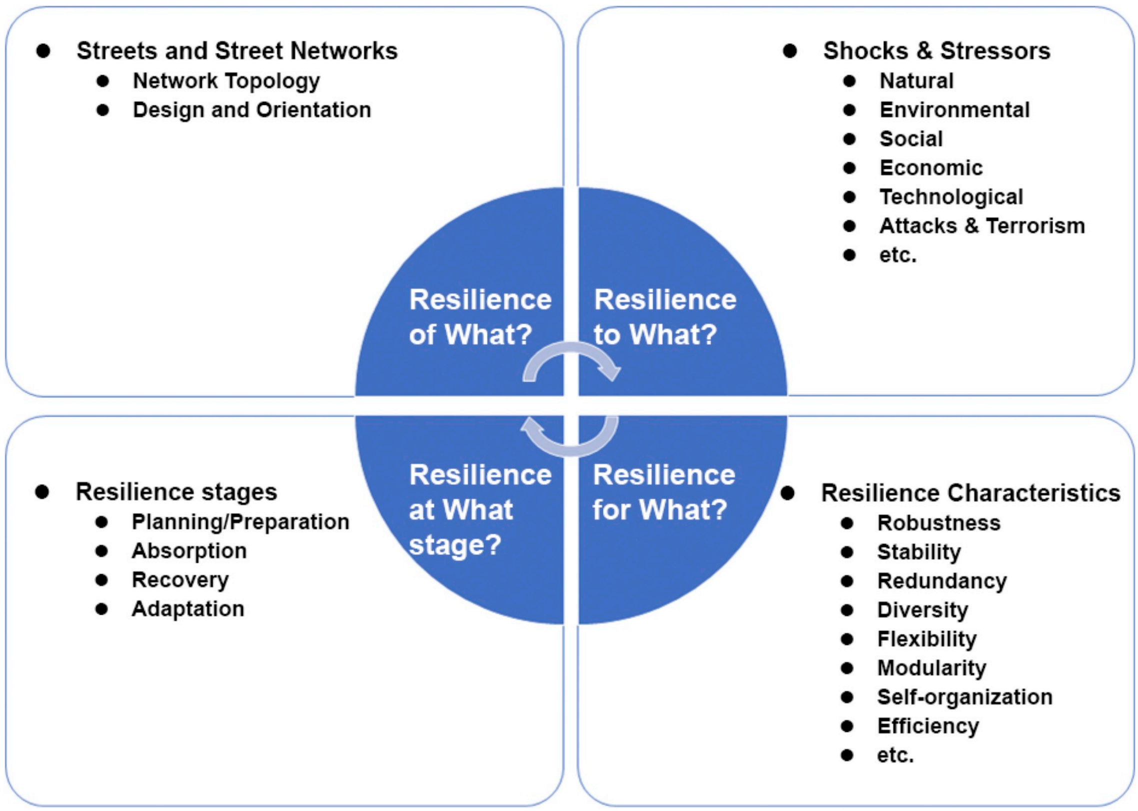

Fig. 1. The proposed analysis framework.

Table 1
Major centrality and connectivity measures.

Measure	Expression	Note	Reference (s)
Centrality measures			
Degree centrality	(1) $C_i^D = \frac{\sum_{j=1,\,N} a_{ij}}{N-1} = \frac{k_i}{N-1}$	The larger the number of connections between a node and other nodes in the graph, the higher its importance in terms of degree centrality.	[29,34,35]
Closeness centrality	(2) $C_i^C = \frac{N-1}{\sum_{j=1;j\neq i}^{N} d_{ij}}$	Indicates how near an intersection (node) is to all other reachable intersections in the city along the shortest paths of the network. C_i^C of node i is the inverse average distance from it to all other nodes in the network.	[23,27,34,36]
Betweenness centrality	(3) $C_i^B = \frac{1}{(N-1)(N-2)} \sum_{j=1;k=1;j\neq k\neq i}^{N} \frac{n_{jk}\ (i)}{n_{jk}}$	Nodes that are traversed by a larger fraction of shortest paths between all pairs of nodes in the network exhibit higher betweenness centrality.[1]	[23,27,31,34,36,38]
Street network efficiency	(4) $E = \frac{1}{N(N-1)} \sum_{i,j\in N,\ i\neq j} \frac{d_{ij}^{eucl}}{d_{ij}}$	It is the average normalized efficiency of all possible couples of nodes in the network.	[17]
Straightness centrality	(5) $C_i^E = \frac{1}{N-1} \sum_{j=1;j\neq i} \frac{d_{ij}^{Eucl}}{d_{ij}}$	This measure is used to understand the extent of straightness of the shortest links between network nodes.	[28]
Information centrality	(6) $C_i^I = \frac{\Delta E}{E} = \frac{E[S]-E[S']}{E[S]}$	It can be utilized to understand how exclusion of a link(s) that is connected to a specific node(s) affects the functionality and efficiency of the street network.	[27–29,34]
Connectivity measures			
Characteristic path length	(7) $L = \frac{1}{N(N-1)} \sum_{i,j\in N,\ i\neq j} d_{ij}$	It is the average length of the shortest paths between all possible couples of nodes in the network.	[17]
Cyclomatic number	(8) $\mu = K - N + 1$	Representing the number of circuits in the network, it is an indication of the number of possible routes between two different points in the network.	[39–41]
Alpha index (also called 'meshedness coefficient')	(9) $\alpha = \frac{\mu}{2N-5}$	Related to the Cyclomatic number, it is defined as the ratio of number of circuits (loops) to the maximum possible number of circuits in a graph with the same number of nodes.[2]	[10,39]
Beta index	(10) $\beta = \frac{L}{N}$	It is a measure of frequency of connections and is defined as the ratio of the number of links to the number of nodes (intersections) in the street network.	[39]
Gamma index	(11) $\gamma = \frac{L}{3(N-2)}$	It is another measure of the frequency of links and is defined as the ratio between the number of links and the maximum possible number of links.	[39]

Note: C_i^D- degree centrality, C_i^C - closeness centrality, C_i^B- betweenness centrality, E-street network efficiency, C_i^I- the information centrality of node i, a_{ij} - indicates presence or absence of a link between nodes i and j (1 when there is a link and 0 otherwise), d_{ij} - the shortest distance between nodes i and j, d_{ij}^{eucl} - the Euclidian distance between nodes i and j, N- is the total number of nodes, k_i - is the number of nodes adjacent to i, n_{jk} - the total number of shortest paths between nodes/links j and k, n_{jk} (i) - the number of those shortest paths that traverse node/link i, $E[S]$- the efficiency of the street network with N nodes and K links that can be obtained from Equation 4, S'- the street network with N nodes and K-k_i links (following the link removal).

labelled and categorized for the respective street elements. Additional categories were designed for any evidence that is related to inter-linkages and trade-offs. After reviewing all relevant documents, the collected evidence was analyzed to determine whether relationships exist between resilience and the selected street elements. Results of the content analysis are provided in the next section.

3. Streets and street networks

Design and topological and morphological properties of street networks have significant implications for continuous, efficient, and reliable functioning of urban infrastructure [17,18]. Two major approaches for analysis of street network resilience can be distinguished: analysis using the network topology and analysis based on layout and design features. These are explored in the following sub-sections.

3.1. Network topology and resilience of street networks

Resilience of street networks can be examined using the graph theory that represents the network topology in a simple manner [19]. A graph is an abstract representation of pairwise relations between a set of elements in a network. These elements are called nodes (also vertices or points) and the connections between them are called links (also edges, arcs, or lines) [20]. The graph theory has been extensively used to understand the complex structure of street networks [19]. While, in many cases, street networks are not planar (i.e., overpasses, underpasses, tunnels exist in the network), the existing literature is highly dominated by the two-dimensional (2-D) representation of the street networks [20–22]. Acknowledging that the 3-D representation is needed to avoid oversimplification, this review only focuses on planar representation due to the limited availability of studies that take a non-planar approach. Further, street networks can be analyzed using either primal or dual graphs. In primal graphs, nodes and links represent street intersections and street segments, respectively [23,24]. Conversely, in a dual graph nodes and links represent street segments and street intersections, respectively. Dual graphs are extensively used as a basis for space syntax analysis [19,20,25]. However, as Boeing [20] argues, dual graphs overlook important street network spatial characteristics such as length, shape, circuity, and width and, therefore, are not desirable for analyzing performance and functionality of street networks. As will be discussed later, such characteristics affect the ability of street networks to reduce the impacts of adverse conditions. Therefore, this review mainly focuses on the primal graphs.

Optimal functioning of street networks hinges on the number of nodes and links, their capacity, and how they are located with respect to each other. Different topological combinations can be obtained depending on how nodes and links are arranged with respect to each other. Centrality and connectivity are major intertwined measures, related to network topology, that are commonly used for examining performance of street network systems. Comprehensive review of studies that use these measures for street network analysis is beyond the scope of these paper. Interested readers may refer to cited references for more detailed information (e.g., see Refs. [26–28]).

3.1.1. Centrality

Not all nodes/links in a street network have the same level of importance. Centrality measures are, generally, used to measure the degree of importance of specific nodes/links in a street network [29,30]. In methods such as Multiple Centrality Assessment, street networks are presented as primal graphs where intersections and paths represent nodes and links, respectively [23]. Centrality has major implications for resilience of urban form. Making urban services and facilities reachable is the main function of street networks. Street networks should be designed in a way that potential disruptions in some nodes/links do not result in significant loss of reachability in the system in general and in complete disconnect between two locations in particular [31]. Streets with high centrality values indicate a polarization of accessibility in the system. This means that in case such streets are obstructed, other streets in the network may not be capable of appropriately distributing the traffic volume. Thus, due to the high dependency of cities on highly central streets, significant care is needed to maintain the continuity of their functionality [32]. Since this high dependence undermines the resilience of the whole system, it is critical to ensure that there is no glaring dominance of highly central nodes/links in the network. To avoid such a polarization, it is suggested that the extent of centrality is determined using a hierarchic approach that follows power law distribution. This implies having small, medium, and large numbers of high-, moderate-, and low-centrality nodes/links in the system, respectively.

3.1.1.1. Measures of centrality. The relative importance of a node/link in the street network can be measured using different centrality measures. Some of the most common measures are degree centrality, closeness centrality, spinality, betweenness centrality, information centrality (network efficiency), and straightness centrality. These measures are defined in Table 1.

Degree centrality is the simplest centrality measure that shows how many connections a node has (Table 1, Eq. 1). Street networks in many cities are characterized by many nodes with low and moderate degree centrality and few with very high degree centrality. Disruption in nodes/links with high degree centrality can affect reliability of the street network and bring a large part of it to collapse [10,33]. This indicates the importance of having preparatory measures in place to appropriately deal with any disruptions in nodes with high degree centrality.

To augment resilience of urban form in terms of accessibility, it is essential to consider closeness centrality when making decisions about the location of services and amenities (Table 1, Eq. 2). Closeness centrality is an indicator of the ability to reach a location (from other places in the network) within a reasonable time and distance [23,28]. It is critical to place evacuation areas and emergency service facilities such as hospitals, fire stations, and police departments in the vicinity of nodes with high closeness centrality values to improve their accessibility in the time of disaster [42]. In relation to the placement of emergency service facilities, Novak and Sullivan [42] introduce the concept of ‘critical closeness accessibility’. It is argued that significance of each link (and its associated nodes) in the graph is dependent on the relative importance of the nodes (determined by factors such as population around the node, market share, availability of critical infrastructure etc.), the number of shortest-distance connections facilitated by the link, and whether the link is an ‘isolating link’ or not (deactivation of an isolating link as a consequence of adverse events will result in the complete isolation of parts of the network from the city) [42]. To enhance resilience, it is advised to minimize the number of isolating links and avoid placement of critical services near them.

In addition to its utility for emergency response, considering closeness centrality for placement of services and functions will also provide other benefits in terms of travel demand management through reducing spatial disconnection between locations [23].

Spinality is a measure that is closely related to closeness centrality. It indicates the extent of alignment of the built environment with a transport axis and can be measured using the following indicators: the buffer ratio, and the route length ratio. The former is the fraction of the built-up area within a certain distance of major roads. The latter is the ratio of the major road length to the total road length in the area [43]. Effective maintenance efforts are needed to avoid perturbations in roads with high spinality values. However, while such roads make the urban system prone to disruption, it can be argued that concentration of (mixed-use) development along the spine (major transport axis) may improve accessibility to services and enable developing efficient public transportation systems.

Betweenness centrality is another measure used to measure the

relative importance of a node/link in the street network (Table 1, Eq. 3). As locations with high betweenness centrality values lie between many other locations, their role in maintaining functionality of the street network is critical. Any disruptions in such nodes/links will have major ramifications across system [37,44]. For instance, in the New York City the surrounding highways that have high link betweenness centralities are located in floodplains [44]. Simulation study shows that an extreme flooding event will result in the removal of those highways from the road network, thereby significantly affecting its resilience [44]. Defining resilience (adaptive capacity) of a street network as the ratio of margins (difference between capacity and flow of nodes in the street network) that remain following a perturbation to the original margins (before perturbation), Akbarzadeh, Memarmontazerin, Derrible and Salehi Reihani [37] argue that a resilient street network should be able to accommodate the extra flow generated by the removal of one or more nodes. Results of their simulation model indicate that the adaptive capacity is significantly reduced if a certain fraction of nodes with high betweenness centrality values are damaged. Therefore, street network configurations with high maximum betweenness centrality values are more vulnerable to disruptions. In other words, those networks that only have one (or few) dominant central node are not desirable in terms of resilience. Dominant nodes can, for example, be seen in wheel (star)- shaped street networks, where the focal node measures high in terms of betweenness centrality [45]. Drawing on three cases from Portland, Oregon (Fig. 2), Boeing [20] shows how street network type can result in significant changes in the distribution pattern of between centrality. The street pattern of the selected cases can be categorized as orthogonal grid, mixture of curvilinear and rectilinear grid, and hybrid curvilinear configuration (cellular and tree-like), for Downtown, Laurelhurst, and Northwest Heights, respectively. The most important node in Northwest Heights is traversed by 43% of shortest paths. However, for the Downtown case this fraction is only 15%. Therefore, the presence of nodes with high betweenness centrality in the former makes it far more vulnerable to disruptive events that may result in the failure of important nodes.

As efficiency is a central characteristic of resilient systems, improving street network efficiency contributes to the adaptive resilience of urban form. Closely related to closeness centrality [28], the efficiency of a street network is an indication of the extent of directness of links between network nodes (Table 1, Eq. 4).

Efficiency of the street network is maximized (approaching 1), when the average shortest distance between all pairs of nodes is comparable to their average Euclidean distance [17]. . Straightness centrality is a variant of network efficiency and can be calculated using Equation 5 (see Table 1) [28]. Higher straightness centrality indicates less deviation of the shortest link connecting two nodes from the Euclidean line between them [23,27] and it is argued to increase resilience by facilitating a more efficient interaction between the nodes [23,27].

The last centrality measure to be discussed here is, arguably, the most relevant one to urban form resilience. Information centrality is a measure of the importance of a specific node in the network (Table 1, Eq. 6). When a disaster occurs, deactivation and obstruction of a node (s) and/or link(s) is likely to be experienced. Obstruction of high information centrality nodes is not desirable, because if such nodes become bottlenecks when disasters occur, the ramifications will be significant. The properties of all centrality measures are reflected in the information centrality and it has correlations with other centrality measures such as degree, closeness, and betweenness [28]. The high positive correlation between information and betweenness centrality has been demonstrated in a study of urban structure in several self-organized and planned cities [29].

3.1.1.2. Centrality and its association with resilience. Empirical evidence on the association between centrality measures and resilience is scarce. Wang [36] used measures such as 'betweenness centrality', 'closeness centrality' and 'network efficiency' to compare the resilience of street networks of London and Beijing. He also examined how random and intentional attack scenarios that disrupt normal functioning of nodes and links affect the performance reliability of street network systems in these two cities. It was found that the street network system in Beijing (dominated by a grid pattern) is more resilient compared with London (where street network tends to be more dendritic). Due to these structural differences, spatial distribution of centrality measures is different in these two cities. For instance, in London motorways and arterials radiating from city center to its periphery have higher betweenness centrality values. However, in Beijing roads with higher betweenness centrality are ring roads and grid-shaped roads (see Fig. 3). In Beijing, ring roads and grid-like arterials provide better connectivity to minor streets and collectors; thereby facilitating a better distribution of traffic throughout the city (compared with London). To compare these two cities in terms of network efficiency, Wang [36] examined how removing links (street segments) affects the capacity to handle traffic. Simulation results showed that the traffic handling efficiency of the grid-like structure of Beijing drops more slowly than the dendritic structure of London. Therefore, it is argued that the street network of Beijing is more resilient.

While studies cited earlier warn about the potential negative effects of high centrality, the utility of centrality for economic resilience should not be overlooked. As centrality can contribute to economic resilience, commercial and service activities tend to have a higher concentration around nodes/links with higher betweenness and closeness centrality values [46]. For instance, strong positive correlations between street centrality and economic activity have been reported for Bologna (Italy) [23], Barcelona (Spain) [47], and Wuhan (China) [48].

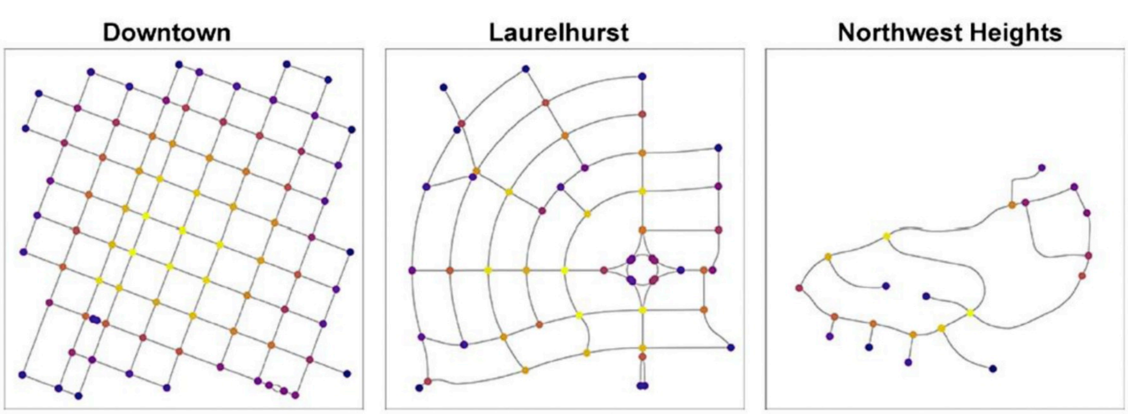

Fig. 2. Distribution pattern of betweenness centrality in three areas of Portland, Oregon. The darker the color, the lower the betweenness centrality (Adapted from Ref. [20]). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

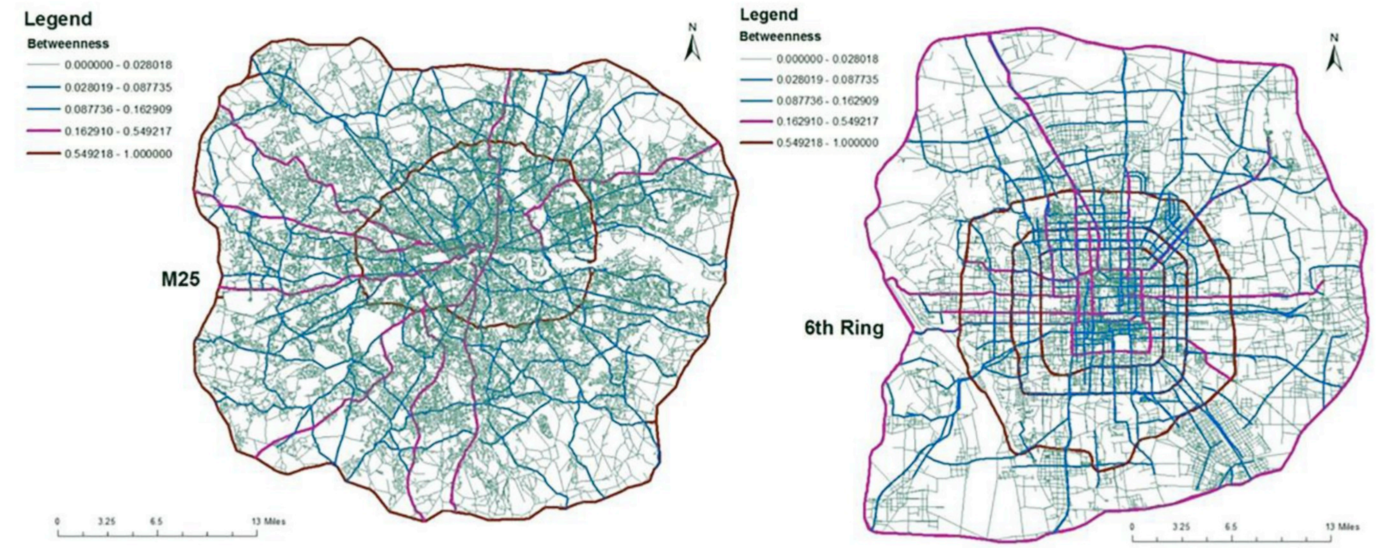

Fig. 3. Spatial distribution of betweenness centrality in London (left) and Beijing (right) (Adapted from Ref. [36]).

Areas that have higher betweenness centrality values are unique locations in the built environment that have a higher potential of being traversed by people and freight trips to other locations in the city. This high potential to attract through traffic increases the possibility of generating business opportunities in areas with high betweenness centrality [23].

Scale hierarchy and power law distribution are underlying characteristics of complex and self-organizing systems and are essential for achieving adaptive resilience. An inverse power law for the relationship between size and frequency of constituent elements can be observed in scale-hierarchic systems. In other words, the frequency of an element is proportional to the inverse of its size [49]. Accordingly, one way to strike a balance between positive and negative effects is to ensure that centrality distribution in the built environment closely follows a power law [23].

3.1.2. Connectivity

Connectivity measures are commonly used to examine the functionality of the urban system under normal and/or emergency conditions. Connectivity can be discussed in terms of the movement of humans/vehicles, as well as the movement of species. The latter is beyond the scope of this study.

Connectivity measures are intertwined with other measures such as centrality and accessibility. Under normal conditions, a well-connected street network is expected to facilitate smooth origin-destination flow, reduce travel distance, and improve accessibility to services, employment, and utilities in a timely, efficient, equitable, and environmental friendly manner. In conjunction with other features such as relatively high density and high levels of mixed-use development, the extent of connectivity can play a defining role in the trip length and mode choice of people [50,51]. People often have a perception of certain trip length thresholds when making decisions to walk or bike. Small changes in the length of the trip can significantly affect their mode choice [50]. This makes enhanced connectivity essential for managing transport demand and for reducing transport-related GHG emissions. High connectivity can also provide social and health-related resilience benefits by fostering active transportation and facilitating a more equitable access to services and utilities.

Under stressful circumstances caused by changing conditions (e.g., due to disasters or increased travel demand), redundant connections are needed to maintain system functionality and accessibility of services [39,52]. Under such conditions, assessing the resilience of street networks should not only involve exploring availability of origin-destination connections, but also include comparison of maximum throughput attainable before and after the event [39].

3.1.2.1. Measures of connectivity. The intersection density, the average distance between intersections, the average node connectivity, the characteristic path length, the Cyclomatic number, and the alpha, beta and gamma indices are commonly used connectivity measures. The simplest measure, intersection density, is defined as the number of intersections (nodes) per unit area. Higher intersection density is associated with higher connectivity. Similarly, shorter average distance between intersections can be an indicator of high connectivity [41]. The average node connectivity is "the mean number of internally node-disjoint paths between each pair of nodes in the graph". It "represents the expected number of nodes that must be removed to disconnect a randomly selected pair of non-adjacent nodes" [20] (p.128). High value of the average node connectivity indicates better connectivity and contributes to resilience of the street network [20]. The characteristic path length (L) is a measure of separation between intersections and lower values indicate better connectivity [17] (Table 1, Eq. 7). However, lower values may not always be desirable. For instance, evidence from Montreal, Canada shows that longer street segments are positively associated with street tree cover [53]. Street tree cover enhances adaptive urban resilience through providing multiple ecosystem services.

A drawback of using *L* for measuring resilience of street networks is that its value becomes infinite as soon as two disconnected nodes exist in the network. This is a condition with high likelihood of occurrence in the aftermath of adverse events such as floods or earthquakes [17].

The Cyclomatic number is a measure of redundancy in the network connectivity (Table 1, Eq. 8). Redundancy of possible routes prevents the street network from major collapse as a result of subtracting a node/link [40]. Higher Cyclomatic number indicates better connectivity. For the purpose of comparison between cities, Cyclomatic number should be calculated per square kilometer [40]. In a planar graph with *N* nodes the maximum number of circuits will be 2N-5 [10]. Other commonly used measures of connectivity are the alpha, beta, and gamma indices (Table 1, Equations 9, 10, and 11, respectively).

It can be understood from the connectivity measures that increasing the number of intersections and street segments (links) contributes to enhanced connectivity and porosity. Achieving high street connectivity depends, to a large extent, on the size of blocks and the street pattern type. Superblocks detract from connectivity by increasing the distance between intersections.

Street pattern has significant bearing on how connected the street network is. Gridded networks, with small blocks, are characterized by route directness, route continuity, and permeability. Due to these characteristics, they are capable of promoting short pedestrian trips, encouraging active transportation (walking, cycling, etc.), and improving pedestrian service and transit accessibility [43,54].

3.1.2.2. Connectivity and its association with resilience. Street connectivity influences pedestrian accessibility. Pedestrian route distance would be greater in less-connected streets. It is therefore advised to pay attention to the importance of connecting minor and major routes in the pedestrian hierarchy. Appropriate connection between minor and pedestrian routes to major transit streets is critical for facilitating effective and efficient access to public transit [16].

Street connectivity augments permeability of the urban fabric. This can contribute to reducing Vehicle Kilometers Travelled (VKT) and enhancing urban walkability. There is extensive evidence showing that increased intersection density is strongly associated with lower VKT [51,55,56]. For instance, simulating the effect of increasing intersection density on the VKT (for a prototype mixed-use neighborhood in Calgary), it was found that there is a negative correlation between intersection density and frequency of trips by private vehicles per day. It was estimated that a 50% increase in the number of intersections per street km can result in a 5% reduction in the VKT (thereby reducing GHG emissions) [57]. Walkability can improve property values and enhance vibrancy and economic viability of cities [58]. Using economic data and data from several social media tools to explore the links between urban form indicators, economic vitality, and housing price; it was found that intersection density has the most significant and positive impact [58].

Intersection density contributes to adaptive urban resilience by fostering networking activities and social encounter. This was demonstrated in a study on resilience of communities along the Gulf Coast. Investigating the impact of different urban form variables, including land use mix, residential density, presence of parks, and intersection density, it was found that intersection density has the greatest effect (followed by net residential density, historic site density, the density of social networking organizations, and land use mix) [59].

Connectivity at the micro-level can also provide benefits for environmental resilience. For instance, integrating greenery into a well-connected street network has merits for reducing the heat island effect. Other benefits can also be accrued; Brody, Kim and Gunn [60] argue that higher connectivity results in smaller total area of impervious surface in neighborhoods and therefore reduces the risk of flooding caused by stormwater runoff.

It is worth noting that the optimal structure of street networks varies depending on what their main purpose and function is. Increasing redundancy (in terms of connectivity) to the maximum level could be desirable for transport demand management and smooth evacuation in the aftermath of disasters. However, Bourdic, Salat and Nowacki [40] raise the concern that maximizing the number of intersections may turn the city into a maze and leave limited space for other uses (e.g., parks, open space, buildings, etc.). As shown by Kevin Lynch in his seminal work, The Image of The City, providing a satisfying urban from hinges on proper arrangement of different constituent elements (i.e., paths, edges, districts, nodes, and landmarks) [61]. Therefore, to enhance legibility and avoid "turning the city into a maze", the interrelations of intersections with other elements should be considered.

Maximum connectivity may also increase the maintenance costs and intensify undesired effects by causing problems such as swift spread of epidemics [33]. Maintenance costs may increase due to the possible increase in vehicular and pedestrian surface area. Maximum connectivity, that results in crowded pedestrian environments, can also exacerbate the spread of diseases and epidemics. Accordingly, adding redundant links should be done in a careful manner. It is suggested that leaf-like street networks that are governed by power law distribution are effective for preventing rapid dispersal of catastrophic fluctuations. As explained in the following section, such networks have few major long-range links that are weakly connected and many short-range links that are strongly connected. The weakness of long-range connections helps absorb the intensity of catastrophic fluctuations and reduce their speed of dispersal [62].

3.1.3. Resilience of two common street network patterns

3.1.3.1. Gridded networks. Gridded networks that are characterized by short street segments and frequent intersections, provide better capacities to adapt to adverse events and changing conditions by integrating flexibility and redundancy features into the network (higher Cyclomatic number compared to other street patterns such as dendritic layouts) [63]. Such a configuration enhances connectivity and would make adaptation to future changes easier as it would be possible to close one street segment (for maintenance or other purposes) without having significant impacts on the flow of people and vehicles. Under such circumstances, the redundant connectivity of the grid pattern provides other alternative options for circulation of people and vehicles [63]. As cases in point, the redundant connectivity of the grid network contributed to better performance during the absorption and recovery phases following the 2010 and 2011 earthquakes in Concepción and Christchurch, respectively [14,64]. As it was needed to cordon off some street segments, the redundancy of the gird network proved essential for maintaining traffic flow through alternative routes [64].

Given the more even distribution of node/link centrality values in the gridded networks (a smaller fraction of shortest paths traverse an average node/link in the gridded networks compared to other patterns such as dendritic), they are less prone to disruption due to failure in one or few nodes/links [20]. The gridded networks' higher resilience to disruption is further strengthened by their higher level of connectivity. Most intersections in the gridded network are 4-way (unlike dendritic networks where many 3-way intersections and dead ends exist). This implies better connectivity as more streets emanate from each node [20]. The dominance of 4-way intersections contributes to the resilience of gridded networks (to obstruction of some street segments) through providing redundant connectivity. Since the average node connectivity is relatively high in bi-directional gridded networks, a larger number of nodes must fail for two randomly selected nodes to be disconnected [20].

The higher connectivity of gridded networks has also been demonstrated using other connectivity measures. In a modelling study conducted by Zhang, Miller-Hooks and Denny [39], numerical experiments were conducted, using measures such as origin-destination connectivity (before and after disaster) and the ratio of maximum throughput[3] attainable post-disaster to the throughput achievable pre-disaster, to evaluate resilience of different transportation network topologies. It was found that higher cyclicity improves resilience by building more redundancies into the network. More circuits indicate higher redundancy and this helps maintain adequate levels of connectivity and accessibility in case one (or more) links are damaged and subtracted from the street network. It was found that, overall, the following street network typologies provide better performance in terms of resilience (descending order of performance): 'complete', 'matching pairs', 'complete grid', 'diamond', 'grid'. Weakly connected typologies

[1] Link weights (e.g. travel time, congestion, link length) can be taken into account in calculating betweenness centrality [37] M. Akbarzadeh, S. Memarmontazerin, S. Derrible, S.F. Salehi Reihani, The role of travel demand and network centrality on the connectivity and resilience of an urban street system, Transportation (2017). However, it is demonstrated that the traditional betweenness centrality (all link weights equal unity) is best suited for analyzing resilience of urban street system [37] ibid.

[2] Zero for tree-liked patterns and 1 for complete graphs.

[3] The amount of goods and materials that can be transported through the street network.

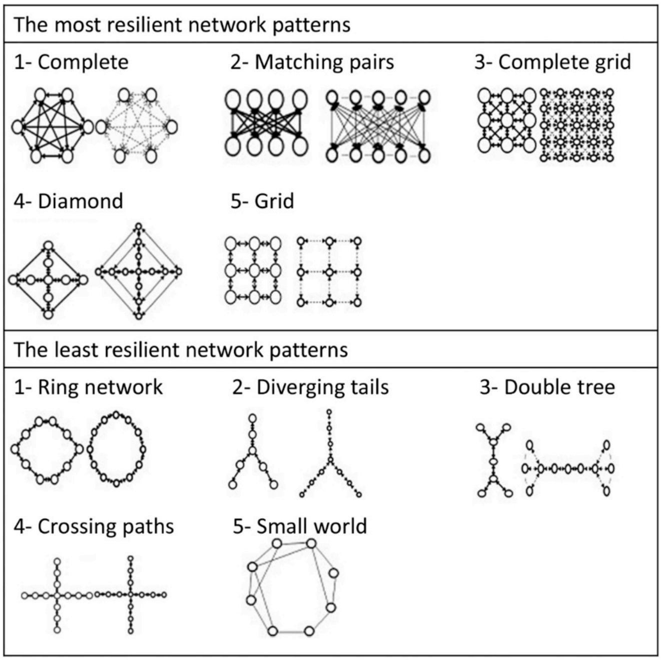

Fig. 4. Resilience of different types of transportation networks analyzed by Zhang, Miller-Hooks and Denny [39].

such as 'small-world' and highly linear typologies such as 'diverging tails' and 'crossing path' performed comparatively worse [39] (See Fig. 4 for a schematic presentation of these network types).

The Christchurch and Concepción cases explained earlier also show that gridded networks of continuous and wide streets reduce the risk of street closure and provide legible and unobstructed evacuation routes [14,64]. The utility of grid pattern for emergency response and evacuation purpose is already shown in the literature [14,65,66]. The Concepcion case shows that the gridded network of wide streets is more permeable and navigable compared with the non-gridded network of narrow and winding streets and is therefore favorable for achieving a rapid and effective evacuation [14]. Arguing that open spaces that are heterogeneous in size (heterogeneity of the urban form is critical for spreading out risk and dealing with uncertainties [67]), and homogeneously distributed across the city are more suitable for enhancing the capacity of cities to provide access to facilities and emergency services, Villagra, Rojas, Ohno, Xue and Gomez [65] found that the regular grid pattern which is better implemented in Concepcion is more suitable for providing open spaces in a homogenous fashion across the city. It is worth adding that heterogeneity (size and functional) of open spaces will also contribute to resilience because it allows people and communities with different sheltering and recovery needs to choose appropriate sites for addressing their specific needs [14].

Finally, in conjunction with other design measures such as mixed-use development, better connectivity provided by gridded networks can improve access to transit, reduce walking distances, and improve urban walkability [68]. Thereby, gridded networks may reduce the risk of pedestrian exposure to extreme weather conditions (e.g., exposure to extreme heat in the case of Los Angeles) [68]. However, arguments about the potential of gridded networks for reducing transport demand and improving walkability assume that people in relatively dense and highly-connected areas tend to walk more. This may not be always the case as high connectivity provided by gridded networks can also generate more short automobile trips and intensify externalities such as congestion and GHG emissions [43,54].

3.1.3.2. Dendritic networks. Dendritic patterns are common in urban systems [69]. As argued by Alexander [69], this is mainly because human mind has a limited capacity to comprehend and process the full complexities of the urban system and has the tendency to use the dendritic pattern to simplify such complexities. For instance, many electricity transmission networks in cities have a dendritic structure. The transmission system includes large scale remote power plants, and high and low voltage transmission lines [62]. A similar structure can be observed in some street networks. In a dendritic hierarchy, streets are arranged in a way that resembles the structure of a tree. The resilience of dendritic patterns has been discussed in many studies. Batty [33] uses the tree as a metaphor to explain the importance of appropriate design of urban networks to maintain robustness and redundancy of cities. Disruption in some parts of a tree (e.g., broken upstream branches) can result in a loss of functionality in other parts. Such a significant loss of functionality can occur when the number of circuits in the network is limited (related to the Cyclomatic number and the alpha index). Enhancing connectivity through having circuits in a network is critical for addressing this shortcoming [33,62].

The dendritic hierarchy of urban streets results in the high dependence of components at the lower-scale (e.g., blocks and neighborhoods) to processes and inputs that originate from points upper in the hierarchy. This diminishes modularity of the system, increases the possibility of knock-on effects and chained reactions, and undermines the flexibility and self-organization capacities at the lower scale (i.e. blocks and neighborhoods) [70]. Such a hierarchy can be observed in sprawling cities. In fact, it is argued that dendritic road networks can result in the dispersal of urban activities and inadvertently contribute to suburban sprawl [67]. Urban sprawl, in turn, detracts from resilience [71].

The tree-like pattern is not of itself undesirable and criticizing it due to its lack of connectivity and access constraints should not be interpreted as the complete dismissal of its potentials and qualities. The hierarchy found in the tree-like patterns (relations between truck, branches, twigs) follows the power law distribution. Such a hierarchy, called "natural hierarchy" by Marshall (2004) is a desirable quality commonly found in traditional settlements. Cul-de-sacs, footpaths and narrow roads in tree-liked patterns provide semi-private community spaces that may be used for communal activities [72]. Such communal activities will, in turn, contribute to urban resilience by enhancing social capital. The semi-private space facilitated by tree-like patterns is specifically desirable in some contexts where privacy concerns are more important. In such contexts, there might be a tendency for cul-de-sacs, narrow streets, and limited visual connection between the indoor and outdoor spaces. Under such circumstances, openness and high street connectivity may be in conflict with privacy as a local value [46]. A diverse set of street layouts (of varying depth) can be found in non-grid and tree-like patterns (including footpaths, narrow roads, access roads, local distributors, and arterial roads) [16]. Such diverse patterns provide merits in terms of human scale and aesthetics and can be used to create vibrant walkable environments that contribute to socio-economic resilience at the micro-scale.

The tree-like pattern can be reformed and improved by design strategies that improve connectivity and accessibility by facilitating interconnection of the branches [16]. Such interconnections help designers to avoid creating disjoint groups of urban form elements (e.g., streets, lots, buildings, and neighborhoods) by restricting strict separation of elements and creating some overlaps between them [69]. One reform solution can be connecting cul-de-sac roads to other roads in the network using a set of walking/cycling paths. This way, safety of the pedestrian space in the neighborhood is maintained by keeping the area away from pass-through traffic and at the same time, the neighborhood will be well-connected to the surrounding environment. The availability of pedestrian routes at the micro scale is a merit during the absorption and recovery phases of disaster management. It is argued that pedestrian routes are more suitable than vehicular-based routes for evacuation purposes, as they help avoid traffic accidents and traffic congestion associated with vehicular-based routes (likely to occur

Fig. 5. Connectivity as represented in the structure of tree branches (left) and leaves (right).

during the evacuation process). Pedestrian routes should follow universal design rules to have enhanced accessibility and it is also desirable to widen them (considering the height of the adjacent buildings) and keep them distant from potentially obstructing objects (that may fall and block the routes) [52]. Reforming tree-like patterns will also increase the efficiency of the street network. There is evidence suggesting that increasing the alpha index of the street network (by introducing new circuits) increases efficiency significantly [10]. The optimal level of efficiency can be found somewhere between tree-liked networks (alpha index = 0) and networks that follow the characteristics of a complete graph (alpha index = 1). This is because efficiency will saturate before the number of circuits reaches that of a complete grid [10].

The modified dendritic structure resembles the structure of a leaf. The leaf structure is characterized by a well-connected network of veins, the spatial arrangement of which conforms to the power law distribution and the frequent lower scale veins in the hierarchy connect up sequentially (or directly) to the relatively less frequent higher scale veins (see Fig. 5).

Connectivity as represented in a leaf is more suitable than connectivity observed in tree branches. Characterized by the presence of frequent loops, the cyclicity of venation patterns is much higher than that of a tree structure. The interconnected circuits of a leaf provide redundant connectivity. Cutting a bigger branch in a tree will result in losing all the smaller branches down the hierarchy. However, this is not the case for a leaf. Each small vein in a leaf is connected to several bigger veins and therefore cutting one big vein would cause less harm to the whole structure and the leaf continues to survive as sap flow will be compensated by other veins in the leaf system (through functioning loops that substitute for mal-functioned ones) [49,62]. Furthermore, the hierarchical structure of a leaf and the interconnections between the veins result in a structure similar to that of a semi-lattice that as Alexander [69]argues is much more suitable for grasping the complexities of the urban system. The hierarchical structure of a leaf can inspire the design of urban street networks (as well as other networks such as transport, energy, water, etc.), so that the city features many small connections, fewer medium-sized connections and yet fewer large-size connections [62]. A clear and consistent hierarchy (inspired by leaf structure) also improves connectivity and continuity of the street network, thereby enhancing the legibility and ease of movement in the event of emergency evacuation [16].

3.2. Street design and orientation

Good street design plays a key role in enhancing reachability, permeability, vibrancy, walkability, and safety of the urban environment. Despite this, in conventional planning, streets are mainly designed for vehicular movement and their other essential functions are not sufficiently considered. In addition, by taking blueprint approaches, conventional planning fails to take account of future uncertainties. Therefore, streets may be designed in a way that does not support adaptation to changing conditions and adverse events [14]. Through exploring the evidence reported in the literature, here, I discuss the possible implications of street width, the design of street edges, and the street layout and orientation for urban resilience.

3.2.1. Street width

The optimal width of streets for enhancing urban resilience may vary depending on the context, the geometry of the street canyon, the land use intensity of the area, the type of disaster, and the stage of disaster risk management. In the aftermath of rapid-onset disasters such as earthquakes, that are likely to block parts of the street network, reaching damaged areas is the main priority of rescue teams. According to the literature, wide streets provide better evacuation capacities [14,65] and facilitate faster access of emergency response service and medical aid to the injured people. Evidence of safe evacuation after disasters, that can be attributed to wide streets, has been provided in the literature [14,65,73]. These studies, however, ignore the fact that the height of the buildings adjacent to the street is also an important factor determining the extent of street blockage and should be considered [74]. Therefore, when examining the association between street width and evacuation capacity, it is also essential to take the aspect ratio (H/W)[4] into account. An optimally wide street in a moderately dense area may not be optimal in denser locations (where aspect ratios are higher), because it is likely to be obstructed if high-rise buildings collapse following a major earthquake. However, it can be argued that under circumstances where there is no major collapse/obstruction and streets are cordoned off, the wider the street, the more effective will be the evacuation process. According to the literature, wide streets are also more favorable for meeting the ad hoc needs of people during the recovery process. Evidence from Concepción shows how the street space can be used for setting up temporary shelters near the damaged homes [14]. This allows the neighbors to create small communities and benefit from mutual support. Such community activities can expedite the recovery process. Furthermore, proximity to home gives people a certain level of privacy and protects their properties against looting [14].

As mentioned earlier, adaptability is an important characteristic of resilient systems. Adaptability to technological transformations and changing conditions is another potential merit of wider streets. It is easier to modify the street layout (e.g., changing geometry, integrating

[4] The ratio of the canyon height (H) to the canyon width (W) is called the Aspect Ratio and is the most commonly used measure of canyon geometry.

green infrastructure, etc.) of such streets. Integration of various modes of transportation (e.g., bus or bike lanes, sidewalks, etc.) is also easier when streets are wider [75]. Such an integration provides multiple benefits in terms of reducing externalities of urban transportation. For instance, sidewalks along wide streets can be widened for better placement of trees that provide multiple ecosystem services (e.g., trees can ameliorate microclimate and reduce cooling energy demand) [76,77]. Green infrastructure such as bioswales, and water retaining and permeable pavements can also be integrated for flooding control and stormwater management [78–80]. Evidence from Montreal, Canada shows that wide sidewalks (achieved through large setbacks) have strong positive association with street tree cover [53]. The simulation study conducted for a prototype neighborhood in Calgary, Canada shows that the inclusion of bike lanes in all the streets can reduce transport GHG emission by 8% compared to a scenario where only 5% of the streets have bike lanes. Results also indicate that the inclusion of bike lanes may reduce the number of vehicles per household [57]. Therefore, depending on the context and considering other factors such as density and street canyon geometry, designers should provide appropriate street width to promote multimodal streets where auto-traffic speed is reduced and a safe environment for pedestrians and bike users is created by providing a buffer space between different modes [50].

Widening streets may, however, cause trade-offs in terms of walkability. Lower amounts of walking activity are expected along wide arterial roads that prioritize vehicle movement and do not feature appropriate street tree cover [53]. It may also influence indoor and outdoor climate comfort and may have implications for energy resilience. Street width and the degree to which buildings shade each other (and the street) are determining factors related to energy load in buildings and thermal comfort and heat island effect in the urban environment [50]. Determining street width is a context-sensitive task and wider streets may not be desirable under certain climatic conditions. Wider streets in shallow street canyons have higher global radiation yield [81]. This causes problems in seasonal climates where absolute radiation is very low during winter time and widening streets results in only a small amount of extra heat gain. However, this extra heat gain will be significant in summer and will affect thermal comfort indoors and in the street canyon. Therefore, in shallow canyons, designing narrower streets is recommended to limit indoor and outdoor overheating in the summer [81]. This issue should be carefully considered in hot climates where cooling demand is dominant. However, in temperate climates, such as the Netherlands, where heating demand is dominant, wider streets (especially east-north) are preferable as they maximize the amount of solar heat gain.

Regardless of the climatic conditions, uniform street width does not lend itself to urban resilience. A hierarchy of street networks wherein narrower streets progressively connect up to wider streets is more desirable. Multiple resilience-related benefits can be accrued from paying attention to scale hierarchy in determining width of streets. Structuring streets in a scale-hierarchic manner increases complexity of cities and equips them with a higher capacity to evolve and adapt to changing conditions [82]. Hierarchical urban street networks that display fractal features (many narrow streets and relatively few medium-size and wide streets) are argued to be more efficient [62]. Identical width across the street network implies higher construction material requirements [62] and higher maintenance costs. Further, such a monotonous network may lead to higher travel demand, thereby reducing efficiency in terms of travel patterns.

Having narrow streets, irrespective of the density levels, in the hierarchy contributes to creating human-scale environments. Narrow streets can function as semi-private urban spaces that provide indoor-outdoor connectivity and distance residents from the noise and bustle of urban life. Such streets located in a moderately dense neighborhood provide higher opportunities for people to interact with each other. High-speed vehicle movement is not allowed on narrow-streets and this slower pace of traffic reduces the frequency and intensity of accidents. The shorter crossing distance of narrow streets makes the environment safer for people with mobility limitations. These observations are confirmed in a study by Ewing and Hamidi [83]. They found that high-density developments, characterized by narrower streets, are more effective in providing traffic safety and in reducing fatal motorist-pedestrian accidents. These features of narrow streets also make them safer for children to play with their parents and peers. This can have significant impacts on their development and learning.

3.2.2. *Street edges*

Street edges are the interfaces between streets and the abutting buildings and lots (including their assigned land uses). Appropriate design of street edges is needed to maintain permeability of the built environment and strengthen the connectivity between the indoor and outdoor space [9,63]. Streets that bound neighborhoods, blocks, and sanctuary areas should not function as physical barriers that sever the urban fabric by separating these components of urban form. Modifying street edges (through streetscape improvement measures such as active frontages and sidewalks, tree-lined streets, traffic calming of the streets, mixed use, allocating appropriate levels of density, etc.) can turn streets into active boundaries that facilitate permeability and transversal connectivity across the city [70]. Further, coupled with connectivity measures discussed earlier, modified street edges can facilitate a semi-lattice urban fabric that, as Alexander [69]argues, improves integration between different urban form components.

To contribute to urban resilience, streets should provide both movement and accessibility functions. Developing vibrant street edges could be an effective strategy for achieving these functions. Influenced by planning movements such as the “Neighborhood Unit”, in many cities developed after WWII, accessibility is reduced to the scale of collector and local streets and other thoroughfares are mainly developed with the purpose of providing maximum speed (movement and accessibility are decoupled) [70]. Consequently, this separates streets from street edges and other built environment components and undermines socio-economic functions that streets can provide. Therefore, enhancing street vibrancy is critical to ensure streets provide both movement and accessibility functions.

Street vibrancy has a significant bearing on the socio-economic aspects of urban resilience. It contributes to social capital by fostering social encounters, as a street will have more functions than just being a path to reach destinations [46]. Vibrant streets are also expected to be safer due to the likelihood of stronger social control. Such streets in relatively dense and mixed-use areas (especially at the ground level) encourage retail and commercial activities, thereby attracting visitors from within and beyond the neighborhood and strengthening economic vitality and resilience. In such streets, the visual and physical openness (and continuity) between inner and outer spaces and the availability of social interactions improve walkability and reduce car-dependency by making walking a more attractive and enjoyable activity [46]. Fostering walkability through better design of street edges and sidewalks contributes to climate resiliency by reducing vehicular travel demand. This observation is confirmed in a study showing negative correlation between well-designed sidewalks and VKT [43].

Various factors contribute to building frontage vibrancy. For instance, visual perception has impacts on people's emotions and may influence the willingness to walk. In this regard, Gordon Cullen introduced the concept of Serial Vision to explain how the design of streets and street edges can affect the experience of a moving person and influence their emotional reactions. He defines Serial Vision as the sequential appearance of contrasting views and explains how, when walking through a street, the instantaneous revelation of new views is likely to have positive impacts on human emotions [84]. Therefore, appropriate design of street edges and enriching and maintaining aesthetic qualities of pedestrian space and street edges (i.e., façade structures, materials, architectural design and details, etc.) is essential [46]. An important urban form measure that can be used to contribute to

street front vibrancy is to increase the fraction of street-facing plots and to improve permeability of street edges by having a high number of building entrances along the street [46,63]. To increase the number of entrances that are primarily accessible from the street edge, it is required to have relatively small zoning lots. Conversely, large lots (in super blocks) often result in blank walls with few entrances (longer distance between entrances). Moreover, increasing the number of units along the streets is an important design strategy to increase the "eyes on the street" and make the built environment more resilient against crime [85].

Designing streets as shared spaces is another effective strategy for enhancing street vibrancy. Design concepts such as living streets and Woonerfs are proposed to minimize segregation between different travel modes [16]. Boundaries between roadway and sidewalk areas are faded in such street designs. Sidewalks are lowered to a level close to the adjacent roadway. In other words, curb height is minimized. Designing streets as shared spaces contributes to reclaiming streets as public spaces. As shared spaces, streets are more likely to enhance community resilience by facilitating socialization and community interaction. Through lowering traffic speed, they will also reduce the occurrence of traffic accidents. When designing shared spaces, it is essential to pay attention to universal design principles, in order not to undermine the mobility of pedestrians with mobility challenges.

Protecting pedestrians against undesirable weather effects is important for creating vibrant street edges. This could be achieved by measures such as appropriate design of street canyons, providing shelter spaces within certain intervals, or integrating arcades in the streetscape [86]. Street layout and orientation are important factors to be considered in this regard.

3.2.3. Street layout and orientation

The implications of street layout and orientation (direction of the street axis) are mainly related to energy and climate resilience of cities [87]. The layout of streets and pedestrian pathways, along with other factors such as the setting and the dimensions of buildings and landmarks, may influence people's sense of time and their willingness and ability to walk [86]. For instance, orthogonal and symmetrical streets may be more navigable compared to linear and monotonous streets that continue for a long distance [16]. In addition, visual quality and complexity of the street layout has major implications for peoples' evaluative image of the city [88] and may affect their trip length and mode choice [89]. For instance, meandering and organic street patterns can stretch the imagination of pedestrians and instigate a sense of discovery in them [84]. This will make it easier for pedestrians to walk long distances.

To understand the implications of street layout configuration for indoor energy consumption, Hachem, Athienitis and Fazio [90] conducted a neighborhood-scale simulation study in Montreal, Canada. The following site layouts were considered: straight East-West street with south-facing façade (layout I), layout I curved towards the south (layout II), and layout I curved towards the north (layout III). Results show that units in areas with straight street configuration generally have lower cooling and heating demand compared to units in areas with irregular and curved layouts.[5] Similarly, the heating load of both attached and detached rectangular buildings was higher for the curved layout. Increase of energy loads in the curved layouts is explained by mutual shading effects of units. Increased cooling load for the curved layouts can be explained by higher transmitted radiation[6] (through some windows that are oriented towards the west or east in curved site layouts) in the mornings and evenings during the summer time [90].

Street orientation influences urban microclimate through effects on wind flow distribution and the amount of solar radiation received in the street canyon and its flanking buildings [91–93]. As will be explained in the next paragraphs, streets can be oriented in a way that contributes to reducing building energy use and improving outdoor pedestrian thermal comfort. This will enhance the resilience to heat stress under hot summer conditions and facilitate solar heating during cold winter days. Note that there is mixed evidence regarding the optimum street orientation and the examples provided in the rest of this section are highly context-specific and should not be generalized without considering the geometry of the street canyon, the local context, and the local climatic conditions and parameters (e.g., parameters such as relative humidity, solar radiation, wind direction, and wind velocity). Therefore, the desirable orientation may vary from one context to another [94–96].

There are studies showing that the East-West (E-W) orientation can be desirable in hot-arid, temperate, Mediterranean, and cold climates for reducing building energy use [43,97–99]. This is because in such climates, depending on the aspect ratio, alignment of buildings along the E-W axis maximizes south-facing buildings and increases winter solar heat gain. Due to the position of sun in the sky, summer solar heat gain is also relatively lower compared to other directions [43,97–99]. Evidence from Sacramento, California shows that the summer cooling demand of buildings aligned with E-W streets is lower than those aligned with (North-South) N-S, (Northwest-Southeast) NW-SE, and (Northeast-Southwest) NE-SW streets [99]. However, depending on other factors such the depth of the street canyon and local climatological conditions, streets oriented towards other directions may provide better microclimatic conditions [93,95].

In terms of providing outdoor thermal comfort, van Esch, Looman and de Bruin-Hordijk [81] did a simulation study for the temperate climate of De Bilt, The Netherlands and found that, for 10, 15, 20, and 25 m wide streets, N-S streets receive a certain amount of sunshine throughout the year. Although this is beneficial in the winter, spring and autumn, it might cause problems in the summer (unless appropriate shading measures are considered; for instance, the N-S streets with high aspect ratios will get less sunshine during hot summer days). In summer, E-W direction is preferable as it provides shading during hottest hours of the day. However, the E-W streets received no sunshine during the shortest day of year (Dec 21). Similar results were found under the humid subtropical climatic conditions of Thessaloniki, where the deep E-W canyon was the most favorable in terms of providing outdoor thermal comfort during the hottest hours [93]. However, evidence from Tel Aviv (Israel) contradicts these findings and shows that the N-S direction is more desirable for different canyon configurations [100]. It is worth noting that, as the experiments in cities such as Thessaloniki (Greece) and Ghardaia (Algeria) show, the favorable orientation for achieving outdoor thermal comfort may also vary depending on the time of the day. However, the differences are small in most cases and the higher differences are often observed around midday hours [93,101].

The case of De Bilt shows that increasing street width from 15 m to 25 m results in a 11.8–12.9% increase in the dwelling heat gain for the E-W street canyon direction. By contrast, the same amount of street width change resulted in a much smaller increase in heat gain for the N-S direction (2.0–2.8%) [81]. Therefore, as E-W streets are less sensitive to variations in aspect ratio (H/W) than N-S ones, in hot-arid and temperate climates it is suggested to have wide E-W streets (low aspect ratio) to increase winter solar gain and narrow N-S streets (high aspect ratio) to increase mutual shading benefits at summer [97,98]. Due to the position of sun in the sky, unobstructed E-W facades (north-south street) receive the highest amount of radiation during hot summer days. Mutual shading by increasing the aspect ratio reduces the direct and diffuse solar radiation received by buildings and the ground surface [98]. The cooling benefits of N-S oriented street canyons, with high aspect ratios, has been demonstrated under the temperate climate of the Netherlands [102], semi-arid climates of Constantine City and Ghardaia

[5] Note that, generally, heating load and cooling load are associated with winter heating demand and summer cooling demand, respectively.

[6] Refers to the passage of solar radiation through the windows.

(Algeria) [101,103] and Sede-Boqer, Israel [98], sub-tropical and humid climate of Taiwan [91], and hot and humid climate of Dhaka, Bangladesh [104], and Cuba [105].

Under hot and dry climatic conditions, temperatures drop significantly at night and nocturnal cooling is not a major concern. However, it should be noted that deep narrow canyons in other climates (e.g., sub-tropical and humid) can lead to nocturnal urban heat island (as the street level wind flow is restricted and the stored heat is trapped in the deep street canyons) and necessitate intensive air conditioning [98]. A case of worst comfort conditions (of N-S streets) for hot-humid climatic conditions has been reported for Guangzhou. But, the authors explain this contrasting evidence by the fact that unlike other studies, the buildings along the N-S street are facing south and a wide space exists between them that may result in higher sunshine reception [92]. More research on the impact of street orientation on thermal comfort in humid climates is needed.

Prevailing wind directions should also be considered, when making decisions about street directions, to benefit from ventilation effects and minimize potential damages from strong windstorms [93,106]. Deep street canyons that are parallel with the prevailing wind direction tend to enhance street-level thermal comfort in the summer by augmenting wind speed through the wind channeling effect [91–93]. Higher wind speed in the street canyon may also reduce indoor cooling demand by dissipating heat accumulated in the canyon and facilitating convective heat transfer[7] through building envelopes [91]. By contrast, the summertime thermal comfort conditions are likely to deteriorate in deep street canyons perpendicular to the prevailing wind direction. High buildings function as barriers to ventilation in such street canyon configurations [91]. In the winter, however, such street canyons are favorable for providing pedestrian thermal comfort [93]. Simulation results in Sede-Boqer and Tel Aviv (Israel), The Island of Tinos (Greece), and Taiwan indicate that the impacts of wind exposure are less significant compared to the mutual shading/solar radiation impacts [91,96,98,100]. In other words, providing mutual shading and limiting incoming solar radiation are more effective measures than wind exposure for reducing cooling energy demand and should be prioritized. However, cooling benefits achieved through convective heat exchange can still be considerable. In Sede-Boqer, streets parallel and perpendicular to the prevailing wind direction provided some benefits in terms of reducing indoor cooling load. Cooling demand was slightly lower for facades oblique to the prevailing wind direction (NW-SE) [98]. This can be explained by the possible benefits achieved from natural cross ventilation.[8] Similar results were found from simulation models for the subtropical climatic conditions of Taiwan, where the wind velocity was higher and cooling energy demand was the lowest in SW-NE, followed by SE-NW streets. Cooling energy demand was highest for shallow N-S streets that are perpendicular to the prevailing wind direction [91]. Therefore, creating a desirable wind environment requires careful design of street canyons [86,93]. Detailed analysis of the implications of canyon geometry for urban resilience is beyond the scope of this paper and should be conducted in future research.

4. Discussions and conclusions

Streets and street networks are fundamental components of urban form, and growth and evolution of urban systems is highly influenced by their structure and typology. In addition, due to their long life span, design of streets and street networks has long-term implications for urban resilience. Despite this, the resilience of streets and street networks is an under-explored area within the field of urban resilience. As an initial effort to fill this gap, this literature review provides some theoretical and empirical insights on how the design and structure of these important components of urban form can contribute to/detract from urban resilience.

4.1. Summary and some policy/design considerations

This paper focuses on two broad categories of street network elements: topology and design and orientation. In the topology category, the paper draws on the graph theory to examine resilience of street networks using different centrality and connectivity measures. Regarding the centrality measures, it was discussed that is required to have certain levels of centrality for taking advantage of the economies of scale and for appropriate placement of urban services and facilities. However, due to high dependency of cities on highly central streets, there is need for significant care to sustain functionality of highly central streets under different conditions. Disruptions in highly central nodes/links can bring a large part of the urban system to a halt. This paper suggests determining the extent of centrality using a hierarchic approach that follows the power law distribution. This implies having small, medium, and large numbers of high-, moderate-, and low-centrality nodes/links in the system, respectively. It is argued that such a hierarchic distribution of centrality can contribute to self-organization and adaptation capacities of the urban system.

Discussions based on the graph theory and network topology measures showed that connectivity is also critical for achieving urban resilience. If combined with other measures such as density and mixed use, enhanced connectivity can improve accessibility to urban resources and facilities. It also provides opportunities for reducing automobile dependence and promoting walkability. These, in turn, lead to benefits in terms of socio-economic and environmental resilience.

Based on the network topology measures, this paper analyses the performance of gridded and dendritic networks as two broad street network categories. Results of the analysis show that the desirable street pattern should exhibit the core features of both typologies. For instance, the hierarchic pattern of centrality distribution that can be observed in dendritic patterns is desirable for enhancing resilience. Regarding the dendritic patterns, the analyses show that they lack appropriate levels of connectivity and this shortcoming should be addressed by adding pedestrian and cycling routes. Such routes are likely to be more useful in the aftermath of some disasters such as extreme events. This is because the sudden flock of vehicles to the streets will probably cause congestion and delay effective evacuation in the case of rapid-onset disasters.

The design and orientation category included elements related to street width, street edges, and street layout and orientation. It was discussed that coupling topology measures with appropriate street design and orientation is needed to maximize benefits that can be achieved through optimizing centrality and connectivity measures. Street width and configuration of street edges are critical factors to be considered for good street design. These are particularly relevant to socio-economic vibrancy, walkability, and safety of the built environment. Street width is a significant factor that affects the abilities to absorb and recover from adverse events. It is suggested that a scale-hierarchic street network, wherein narrower streets progressively connect up to wider streets is more desirable. Implications of street layout and the aspect ratio and orientation of the street canyon are mainly related to resilience in terms of energy consumption, indoor and outdoor thermal comfort, and heating/cooling demand management. Although structural factors and design and configuration of the building envelope are the main determinants to be considered, other measures such as layout, aspect ratio and orientation can also play an important role in ameliorating microclimate and should be considered. It should be noted that optimal design and orientation may vary depending on the local climatic conditions.

Four important points can be inferred from the evidence reported in

[7] Convective heat transfer occurs when the heated fluid, such as air or a liquid, moves away from the heat source, carrying heat energy with it.

[8] Natural cross ventilation refers to the natural circulation of air within the building, caused by pressure differences between two building sides.

this review. First, the characteristics and requirements that determine the optimal form of streets and street networks may vary depending on the stage of resilience planning and disaster risk management. Under normal circumstances (pre-disaster), key requirements would be to facilitate rapid, affordable, and low-carbon origin-destination connectivity. Furthermore, the design of streets should contribute to creating vibrant and convivial environments that strengthen community interaction and social capital. However, key requirements will be different in the aftermath of a disaster, when the priority would be to facilitate rapid evacuation and timely access to emergency services and rescue teams. Depending on the risk profile, these may prove to be conflicting requirements. It is essential to find a balanced solution that does not affect the efficiency of urban management activities and practices.

Second, the resilience of streets and street networks is affected by the design, form, and configuration of the other elements of urban form (such as lots and buildings) and vice versa. For instance, development of vibrant street edges hinges on paying attention to the form and configuration of other urban form elements such as mixed use and lot size. Mixed-use development, characterized by small lots contributes to permeability of the built environment, and enhances walkability and street vibrancy. The interconnectivity among the different urban form elements should, therefore, be considered when developing plans and policies for building urban form resilience.

The third point (linked with the previous two points) is related to potential trade-offs that may arise when making interventions to enhance the resilience-building capacity of urban form elements. Trade-offs may occur due to conflicts in purposes and priorities, and varying requirements depending on the type of stressor (disaster) and the stage of disaster risk management. For instance, high centrality is desirable for economic vitality and for the provision of efficient transit services. However, it can create chokepoints in the network when disasters occur. Other examples were introduced in the paper. For instance, short street segments improve connectivity, but also, might hinder the incorporation of street trees and therefore deprive the urban landscape from their ecosystem services. Or, increasing connectivity through redundant intersections facilitates smooth evacuation in the aftermath of disasters, but can cause unwanted impacts such as higher maintenance costs, limited space for other services, and increased probability of the rapid spread of risks (e.g., fire or flooding). Accordingly, appropriate strategies should be used to minimize potential trade-offs and maximize synergies.

Fourth, while defining optimal design parameters and developing specific planning/design guidelines is critical for informing resilience planning, provision of detailed and highly specific guidelines without considering context specificities can be problematic. Therefore, this study only provides a certain number of recommendations that are applicable to any context (see Table 2). More specified guidelines should be developed on a case-by-case basis. It should be reiterated that desirable overall performance may not be achieved by only focusing on single elements and, ideally, interlinkages between different elements should be also considered.

4.2. Gaps and future research directions

This research provides useful insights on how the physical form of streets and street networks is related to resilience. However, much work remains to be done to acquire a more granular understanding. Major gaps and future research directions are as follows:

Table 3 indicates whether, in the reviewed literature, evidence exists on how design and configuration of different street elements can contribute to resilience against different threats/stressors. City actors may use this table to understand the potential associations between street network elements and resilience to different threats and stressors. They can also develop similar matrices to explore the linkages between the physical form of streets/street networks and resilience in their cities. Further, it can be seen that some unexplored areas still exist (shown as blank cells) and future work should deal with these gaps. For instance, the potential associations between network topology and resilience to extreme weather conditions should be studied.

- There is also a lack of research comparing the resilience of different street patterns. Gridded and dendritic networks (as two broad categories) were discussed in this paper. However, street networks are complex and multiple permutations of street patterns can be observed in cities. Marshall [16] suggests that street patterns can be divided into five broad categories: linear, tree, radial, cellular, and hybrid (Fig. 6). Various permutations can be identified under each of these categories. Analyzing these permutations using the measures described in this paper may bring new insights regarding their resilience.
- Different centrality and connectivity measures were introduced in this paper. Examining possible correlations between these measures is warranted to see if some of them can be used as proxy measures. For instance, it can be examined if betweenness centrality can be a proxy variable for other centrality variables.
- Regarding the methodological issues, an important issue to be noted is that type and importance of the street segments and street canyon (e.g., street width, canyon geometry) should be considered in computing centrality measures. There is evidence suggesting that considering road width is essential for having a more precise determination of the centrality values [48]. More work is needed to examine the importance of considering other features, such as street canyon geometry, in computing centrality values. Further research is also needed to understand the association between street width and centrality. These two may not necessarily be associated as the analysis of the street network of Buenos Aires shows [107]. However, there is evidence suggesting that centrality measures exhibit strong correlation with economic activity and land use density (e.g., floor area ratio, building coverage ratio, and the ratio between open space and total floor area) [48,108]. Therefore, it can be argued that planners should increase economic activities and building density near streets with higher centrality values in order to achieve efficiency improvements. Under such circumstances, centrality values may be used as a basis for determining street width and aspect ratio. However, in the real world it cannot be stated with certainty that density will be higher around high-centrality streets and intersections. Other factors such as transportation and rent costs will also influence the decision of people and businesses to move to high centrality locations [109]. Therefore, further research in this area is also suggested.
- Existing research tends to simplify street network representation by taking a planar approach. Since in real world many street networks are non-planar [21], it is critical to conduct further research using non-planar approaches to avoid oversimplification of the street network representation.
- Street width should not be studied in isolation from the depth of the street canyon. Therefore, further work is needed to elaborate on the implications of aspect ratio for urban resilience.
- The selected elements are often studied in an isolated manner and their interactions with each other and with other urban form elements are not examined. Further research is warranted to address this gap. For instance, the implications of the potential interconnections between centrality/connectivity and mixed-use development should be studied.
- The reviewed literature mainly focuses on natural and environmental threats and addresses resilience dimensions related to infrastructure and environment. Other types of threats and also socioeconomic dimensions of resilience should be further studied in the future. In addition, non-physical factors are essential and should be considered when making efforts to enhance urban resilience.
- An important issue to be emphasized is that the increasing

Table 2
Important planning/design considerations.

Element	Recommendations
Centrality	- Avoid building high-centrality links/nodes on risk-prone areas (e.g., floodplains) - Prioritize and ensure the regular maintenance, upgrading, and repair of high-centrality links/nodes - Place evacuation zones, emergency service facilities, and amenities near high-centrality nodes/links - Promote mixed-use development around high-centrality nodes/links - Improve consistency of link/node centrality distribution with the power-law distribution
Connectivity	- Include redundant connectivity in the street network to maintain service accessibility and to facilitate smooth evacuation in the immediate aftermath of disasters - Improve connectivity (in conjunction with other measures such as high density and mixed use) to enhance accessibility and to improve walkability - In disaster-prone areas, gridded networks, with small blocks, are more desirable for improving emergency service accessibility and for facilitating rapid evacuation. Gridded networks are also recommended for achieving benefits related to the other dimensions of resilience (environmental, social, economic) - Compared with dendritic networks, gridded networks are less vulnerable to potential disruptions in some parts of the street network - Gridded networks improve accessibility to public transportation - Reform tree-like patterns to improve their connectivity (e.g., by adding walking/cycling paths to connect cul-de-sac roads to other roads in the network) - Locate amenities such as parks, open spaces and communal places near highly connected streets and intersections
Width	- When determining the street width, pay attention to the point that vehicular movement is not the sole function of the street and its social, economic, and environmental functions should also be considered - Appropriate street width improves evacuation and recovery processes, facilitates creating multi-modal streets, and allows adaptation to technological transformations and changing conditions - Consider type of the threat/stressor, street canyon geometry (aspect ratio), and population density of the area for determining the optimal width - Pay attention to the scale hierarchy and the power law distribution when determining the spatial arrangement and distribution of the street width
Edges	- Modify street edges, through streetscape improvements, to ensure that streets provide mobility, accessibility, and socio-economic functions - Promote mixed use, specifically at the ground level - Pay attention to the concept of serial vision - Pay attention to the block size to achieve desired levels of permeability - Pay attention to the size of zoning lots to increase the number of units along the street - Enhance the visual and physical openness (and continuity) between inner and outer spaces - Increase the fraction of street-facing plots - Wherever possible, design streets as shared spaces (e.g., by applying traffic-calming measures and through concepts such as the Woonerf concept) - Integrate greenery and green infrastructure into the design of edges and sidewalks
Layout and orientation	- The optimal orientation of streets (for improving outdoor thermal comfort and for reducing building energy use) is highly dependent on factors such as the aspect ratio, local climatic conditions, relative humidity, solar radiation, prevailing wind direction, and wind velocity. Therefore, it should be specified on a case-by-case basis - The incoming solar radiation, followed by the wind exposure are two important factors that should be considered when determining street orientation and designing street canyons - In seasonal climates, orientation and aspect ratio of the street canyon should be designed in a way to maximize shading and wind flow in the summer but maximize solar exposure and minimize wind exposure in the winter. - Reform monotonous streets that continue for a long distance by improving their visual qualities and by enhancing their navigability

Table 3
Availability of evidence in the reviewed literature on the resilience of the selected street network elements to various threats and stressors.

Potential threats and stressors \ Street network elements		Network Topology		Design and Orientation		
		Centrality	Connectivity	Width	Edges	Orientation
Natural	Earthquakes	■	■	■		
	Floods and tsunamis	■	■	■		
	Fires and wildfires		■	■		
	Storms and hurricanes			■		
	Other natural disasters such as landslides, etc.					
Environmental	Climate change (energy consumption, GHG emissions)	■	■	■	■	■
	Extreme weather (extreme heat and cold, heat island, etc.)			■		■
	Resource scarcity (energy, water, etc.)		■			■
Social	Social issues (e.g., lack of interaction, crime, etc.)	■	■		■	
	Health related issues		■	■	■	
Economic	Economic risks (e.g. recession, competitiveness)	■	■	■	■	
Technological	Changing circumstances (technological, etc.)			■		
Attack & terrorism						

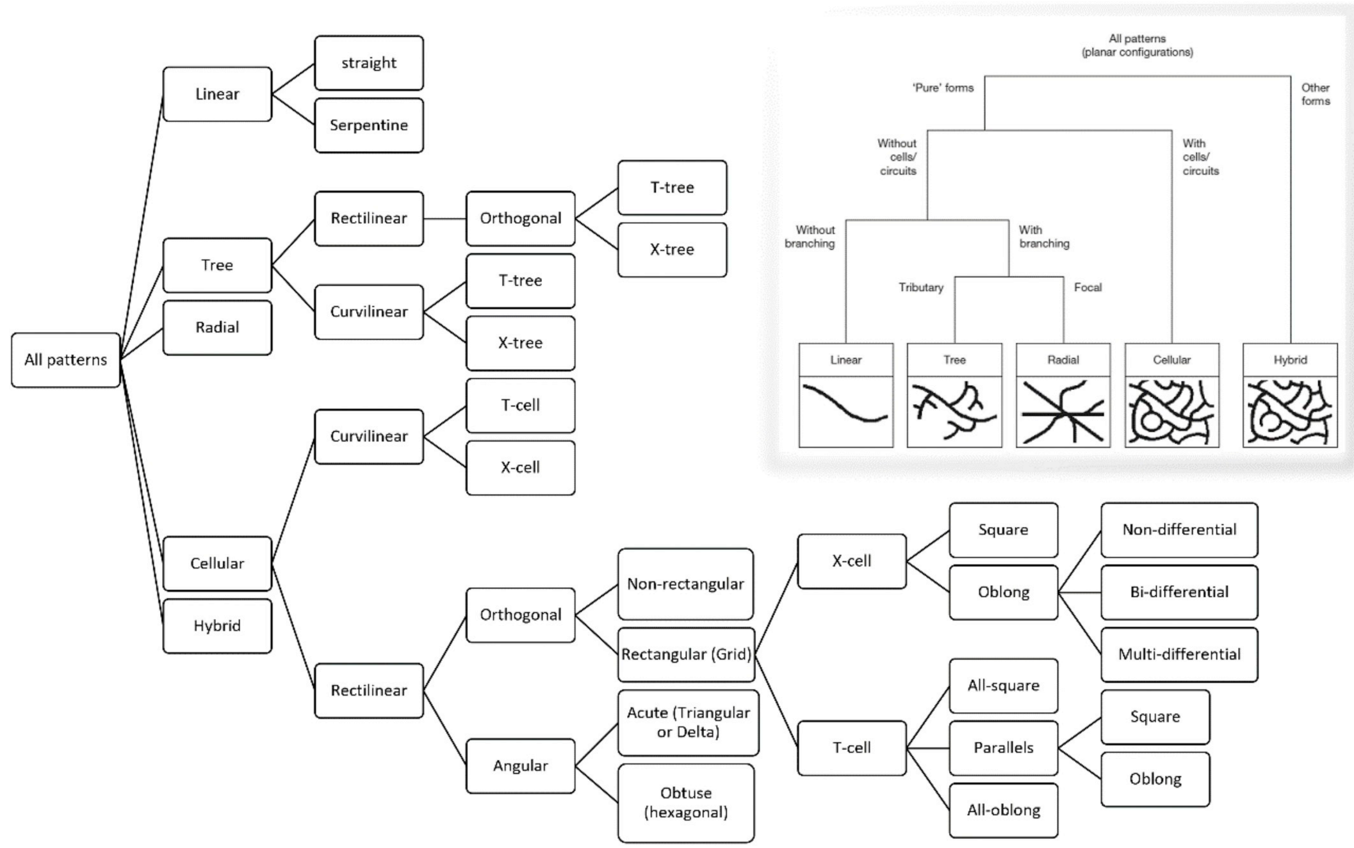

Fig. 6. A general taxonomy of street patterns (adapted from Marshall [16]).

availability of computational tools (e.g. the DeCodingSpaces Toolbox[9]) and open access (big) data (e.g., through platforms such as the OpenStreetMap[10]) provides an unprecedented opportunity to do more context-based analyses of street networks and to also conduct analyses at larger scales (e.g., see Ref. [22]). These capacities should be further explored in the future research.

- Finally, it should be mentioned that this study only focuses on some urban form elements. There are many other urban form elements that influence resilience of cities. Implications of those elements for urban resilience should also be studied in the future.

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Appendix A. Supplementary data

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